A SUMMARY OF RESEARCH ON

MICROWAVE PROPAGATION OVER OPTICAL PATHS

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Prepared Under
National Aeronautics and Space Administration
Research Grant NGR 25-001-007

(NASA-CR-71819) A SUMMARY OF RESEARCH ON MICROWAVE PROPAGATION OVER OPTICAL PATHS (Mississippi State Univ.) 22 p

N76-70913

Unclas

00/98 29460

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March 29, 1966

N67-87188

FACILITY FORM 602

~~X66 36117~~ (ACCESSION NUMBER)	(THRU)
22 (PAGES)	2A (CODE)
CR-71819 (NASA CR OR TMX OR AD NUMBER)	07 (CATEGORY)

The results of a literature search, which was conducted to determine what research had been accomplished toward ascertaining the propagation reliability for electromagnetic frequencies from approximately 1 GHz through visible light frequencies, are presented. Summaries of propagation studies having results that are pertinent to optical paths (i.e., line-of-sight paths) are presented, with notation as to the geographical locations of the studies, their operating frequencies, their path descriptions, and the time of year these data were obtained.

SUMMARY OF LITERATURE

Ref.	Date of Study, Frequency or Wavelength, Path Length, and Location	Results and Conclusions
1.	1930* 5 cm wavelength Theoretical analysis (no particular path)	The effect of rain, fog, or clouds on propagation of short radio waves was studied. A conclusion was that for waves greater than 5 cm in length (or $<$ 6000 MHz) the effect of ordinary rain or fog on absorption is negligible.
2.	July, August 1944 1 cm; 3.2 cm; 1260 feet for the 1 cm link; 900 feet for 3.2 cm link New Jersey	It was concluded that due to rain, the added path loss at 3.2 cm is 1.05 db/mi/mm/hr of precipitation.
3.	April 1944 6 mm wavelength 1200 foot path New Jersey	Rain was measured at the receiving end by one rain gauge. It was concluded that in terms of average rainfall in the middle temperate zone the one-way loss at this wavelength will be less than: .5 db/mi 97% of time 1.5 db/mi 98% of time 6.0 db/mi 99% of time

*Publication date.

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4.	June - October 1944 3 cm wavelength 24 mi and 13 mi paths New York	The investigator concludes that no important difference exists between horizontally and vertically polarized waves in the 3 cm band over the paths used. Vertical plane variations are found to be more common and more pronounced. Variations ranging to 1/2 degree as compared with horizontal plane variations of less than 1/10 degree were present.
5.	April 1946 10.7 cm and 3.2 cm wave-length. 27 mi land Suffield, Alberta Canada	A very marked and progressive improvement in correlation was observed in going from poor to fair to good horizontal uniformity of meteorological conditions, giving considerable support to the commonly accepted diffraction formulae. It appears that statistical forecasts of the probability of abnormal radar ranges, based on past observations, are practical. However, useful day to day forecasts appear to be very difficult.
6.	1943 - 1945 9.2 cm wavelength 61 km path England	In comparing meteorological data with received signal data, it is concluded that a lapse of water vapor content with height gives favorable propagation characteristics while an increase of water vapor content with height gives poor characteristics.
7.	1946* Statistical and Theoretical analysis	The refractive index varies logarithmically with height. Reflections are possible from a discontinuity of the dielectric constant as small as 10^{-5}. Data shows that this discontinuity does occur.
8.	Feb. 1943 - Feb. 1944 45.1, 474, 2800 MHz 42.5 mi optical path 70.1 mi nonopt. path New York	Refraction was found to be greater in the summer months. The strongest periods of refraction occurred at night or in early morning. Refraction was not evident when the average wind velocity was greater than 13 miles per hour. A study of weather conditions during the periods of strongest refractions indicated that roughly 60 per cent of the gradients were of the frontal type. Approximately 60 per

*Publication date.

(continued)		cent of the gradients were higher than 100 feet above the earth's surface. For the optical path, reductions of field strength increased with an increase in frequency. For the nonoptical path increases of field strength increased with an increase in frequency.
9.	March - April 1945 3 cm and 9 cm Ocean path up to 80 mi. Antiqua, B.W.I.	An extremely low-lying surface duct, averaging in height between 20 and 60 feet over the sea, persists in the trade wind regions. The height and strength of this duct varies with wind speed; lower winds produce a higher but weaker duct. Changes in wind speed have no clear effect on the total M deficit which is determined essentially by the temperature and humidity of the air mass as a whole. Passing squalls and rain showers do not wipe out the duct or decrease the received signal. The duct is not present over land but is destroyed within about 1/4 mile from the windward shore. For 9 cm waves, stronger signals are attained with higher antennas up to 100 feet. For 3 cm waves, antenna heights of very low elevation (6 to 15 feet), give stronger signals on longer ranges.
10.	1947* Statistical and Theoretical study 30 MHz (no particular path)	The effects on propagation due to antenna heights, earth's curvatures, hills, buildings, etc., were discussed for frequencies above 30 MHz.
11.	July 1943 - Sept. 1945 3.2, 6.5, 10 cm 40 mi optical path New York	No attempt was made to make meteorological measurements. Periods of greatest fading extended from about midnight to sunrise. Transmissions were most stable during noon hours. It appears that when the atmosphere is well mixed as in windy or rainy weather that transmissions are most steady. Calm and still air is a condition conducive to stratification and duct formation (hence fading increases in the evenings).

*Publication date.

12.	1948* Statistical Analysis X-band (3.2 cm) United States	An attempt to determine the extent of rain attenuation for X-band radar at various localities in the United States was made. It was concluded that heavy rain of .4 inches/hr. over the entire path cuts the range for X-band transmission to 50 miles or less.
13.	1946 300 MHz to 4000 MHz 20, 26, 37 mi paths Philadelphia to New York	Slow types of fading are believed to be caused by an upward curvature of the direct wave path. The effect is the same as if the radius of the earth were reduced from normal earth radius; thus, an optical path becomes nonoptical. The earth curvature diffraction approaches knife edge diffraction with increasing frequency. It appears to be a good practice to design microwave systems so that the free space value of signal is received under normal conditions of refraction. For paths that are high above the grazing point, it has been found that diversity reception is very effective.
14.	April 1946 3 cm wavelength 27 mi path Arizona Desert	There was an apparent reflection coefficient, p, for desert sand of between .3 and .8. The results obtained agree with calculations based upon the theory that the magnitude and phase might be calculated on the basis of a direct wave and a reflected wave from a surface.
15.	1944, 1945, 1946 3 cm and 9 cm wavelengths 60 mi oversea path The coast of Great Britain	There appears to be a correlation between the field strengths and temperature differences between sea water and air. It seems that observations on the performance of cm wave equipment may be useful for determining the mean meteorological conditions along a given path. In fact, the authors felt that the observations might be more useful to the meteorologists than to the radio man.

*Publication date.

16. 1949*
Statistical and Theoretical study.
VHF, UHF (no particular path)

It was concluded that ground reflections constitute a dominant influence on wave propagations within an optical range.

17. 1946
1000 MHz to 25,000 MHz.
26 mi and 41.5 mi path
Arizona Desert

The low moisture, hot climate gives rise to ducting with as much as 50 db effects on microwave frequencies over optical and nonoptical paths. Only two conditions were encountered during the investigations: nearly standard refraction in daytime and a small scale duct at night. The author points out that in the daytime the atmosphere is well mixed and that at nighttime cooling results in an inversion in the lower layers of the atmosphere causing a small scale radio duct.

18. Dec. 1946 - Dec. 1947
16.2, 7.2, 4.7, 3.1 cm
42 mi optical
New York

Microwave radio communication performance will deteriorate appreciably and progressively at shorter wavelengths and, at wavelengths of 3 cm and below, shorter path lengths together with nominal increases in transmitter power are indicated if a high degree of circuit continuity is required. Fading is observed with greater prevalence during the summer months and at night as a result of changing meterological conditions. Diversity reception will prove beneficial in reducing the effects of multipath transmission.

19. Statistical Analysis
10, 50 GHz
50 km
Washington, D.C.

A graph is given of attenuation coefficient in db/km versus expected percentage of time per year that the indicated coefficient will be exceeded. For 10 GHz some points on the graph are (1db/km; .01%), (.1db/km; .2%), (.05db/km; 1%), (.026db/km; 3%-50%). For 50 GHz some points are (10 db/km; .01%), (5db/km; 1%), (1db/km; 5%), (.3db/km; 80%).

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*Publication date.

20.	1950* Statistical and Theoretical Analysis	It was concluded that an important factor in cm wave transmission is the variation of the moisture content of the lower atmosphere with height. The permittivity of saturated water vapor is 1.000257. The permittivity of air with saturated water vapor is 1.000806. The permittivity of moist air is 1.0007. All measurements were made at 752 mmHg, 22C., 83% R.H.
21.	1947 - 1950 3, 10, 25 cm 21 mi, 50 mi Atlanta, Georgia	It was concluded that the lower frequencies average less fade out time than the higher frequencies. The rapidity of fluxations was almost directly proportional to frequency. The received signal strength is strongly influenced by the atmospheric conditions for both optical and non-optical paths. However, the optical paths usually show less fading effects than the nonoptical paths.
22.	1951* 1.25, 2.25, 3.2, 10 cm Various locations in the world	Attenuation due to fog, absorption, and rainfall for different climates differs with wavelength.
23.	1949 - 1950 3.2 cm 37 mi Texas	Scattering has the effect of broadening the antenna pattern.
24.	1949 - 1950 3.2 cm 37 mi Texas	The Brooker-Gordon equation (See H. G. Brooker and W. E. Gordon, <u>A Theory of Radio Scattering in the Troposphere</u>: Proc. IRE Vol. 38. pp. 401-412. April 1950) appears to be substantiated by experimental results.
25.	1947 - 1951 4000 MHz 22 mi land and water New Jersey	Propagation characteristics are independent of polarization. For a 400 MHz sweep centered at 3950 MHz, fadings are frequency selective; that is, in the 400 MHz bandwidth no two frequencies undergo fades of the same amplitude at the same instant of time.

*Publication date.

26.	July - Oct. 1950 4000 MHz 22 mi land and water New Jersey	Fades are caused by multipath transmissions as much as seven feet longer than the direct path.
27.	1952* Statistical and Theoretical analysis	90% of ray bending occurs in the lowest 10 km of the atmosphere. The actual refraction differs considerably from the 4/3 earth's radius approximation for the different localities and seasons.
28.	1950 - 1951* Statistical and Theoretical analysis 3.150, 9.350 GHz	Fading activity is shown to be seasonal for both wave lengths. Pseudo-periodic scintillations are shown to be more rapid for the 9.35 GHz wave. Periods of above normal signal strength are explained by the interference of two waves while periods of deep signal depression are probably a result of the interference of three waves.
29.	1952* Theoretical analysis	A method by which a rough earth can be replaced by a smooth earth is given. [Note: The theory is verified experimentally under a certain condition (see Ref. 38).]
30.	1949 - 1951 3.26, 9.2 cm wavelength 39 mi seawater path New Zealand	Deep fades are caused by momentary cancellation of the direct and indirect ray. This results from a combination of lobe-bending and atmospheric turbulence. Fades for the two wavelengths do not coincide timewise.
31.	June - Dec. 1951 1700 to 1850 MHz band 36 mi, 28 mi California	Fading correlates in general with atmospheric stratification. Ground reflections make the receiving antenna height critical. Space diversity should minimize fading. Deep fades for a path having a strong ground-reflection component are not due solely to relative phase changes between the direct and indirect ray. Fading was observed to be more severe on the strong ground reflection path than on the other path.

*Publication date.

32.	1952 Between 0.86 and 26.5 cm wavelength 1000 feet land and 1430 feet sea path Texas	The reflection coefficient increased consistently with wavelength, and decreased with increasing angle, and was higher for horizontal polarization than for vertical polarization. The 0.86 cm signals were very sensitive to roughness of the reflecting surface. The reflection coefficient for ground roughness of a few inches for 0.86 cm was as low as 15% of the value for 9.0 cm. Wind ripples caused a sharp decrease in the reflection coefficient of 0.86 cm waves but had little effect on the longer wavelength. For vertical polarization, the reflection coefficient for 0.86 cm approached that of the longer waves at the higher angles even for rough water. This indicates that the Brewster angle is not clearly defined for rough surface conditions.
33.	1952 850 MHz 1/2 mi increments New York	For a ground based receiver and for transmitters at different elevations, the highest transmitter does not necessarily give the strongest reception at various points along the path.
34.	July, Aug. 1950 3750 to 4190 MHz 30.8 mi path Iowa	Deep fading is frequency selective and is caused by complex multipath transmissions. Deep selective fading at one frequency is accompanied by 6 to 10 db signal depression over the band of the other frequencies. Fading on frequencies separated by 160 MHz or more show little correlation. As frequency is diminished, correlation occurs. Frequency diversity will minimize fading if the frequency can be shifted far enough away.
35.	Oct., Nov. 1952 8 mm wavelength 1 mi over seawater path Scotland	The path is such that reflections from the sea are negligible. Appreciable fades still occurred.

36. Feb. 52 - Mar. 53
1046 MHz
49.3, 70.2, and 96.6 mi
mountain land
Colorado

Ducting sometimes causes a stronger signal to appear at a distant receiver when compared to the signal at the nearer receivers.

37. 1952 - 1953
1400, 3150, 4000, 9200 MHz
227 km optical sea path from Corsica to France.
29 km mountain to mountain path.
France

Signal distribution curves show that at both wavelengths less fading occurs during the winter months. For example, at 1400 MHz the signal level is 20 db below the average level between 1% and 3% of the time. At 1400 MHz fades as much as 80 db were recorded while at 3150 MHz fades as much as 60 db were recorded. At 3150 MHz it is shown that fast fades are almost 100% correlated for both vertical and horizontal polarization. Thus, it is concluded that polarization will not alter fading on this path. Meteorological soundings indicate atmospheric activity when fadings occur. Altitude diversity of antennas changes fading characteristics, thus, altitude diversity will minimize fading.

38. 1954*
400 MHz
United States

The reflection coefficient cannot be predicted by analyzing the path profile.

39. September 1954
955, 1965, 6730 MHz.
20.25 mi land
Shreveport, Louisiana to Latex, Texas

The object of the report was to publish propagation data for the Gulf South geographical area. It was concluded that fades become more frequent but shorter in duration as the frequency increases.

40. 1952 - 1953
92, 100, 192.8, 1046 MHz
optical and nonoptical paths up to 226 mi from high mountain
Colorado

Rayleigh's criterion of roughness, R, is used in conjunction with Norton's (see Ref. 28) method for replacing a rough terrain with a smooth surface to calculate transmission losses. This method is verified experimentally for $R \leq 0.1$. Also, a method for calculating transmission losses for a smooth surface as a function of a linearly increasing refractive index profile is presented. It is shown that the transmission loss for 1046 MHz is appreciable for certain values of refractive index.

*Publication date.

41.	1957* Nonoptical in various localities and seasons	An expression for the refractive index of the atmosphere in N units is given. It is shown that N varies logarithmically with height above the earth (see Ref. 20). Experimentally obtained data shows that N varies considerably with the time of the year and the latitude. The average values of monthly median path loss have a definite correlation. The N variations tend to explain seasonal and climatic signal variations.
42.	1956 - 1957 8.6, 4.3 mm wavelength 3.5 to 61.0 mi path Colorado and Texas	At 4.3 mm the attenuation due to rainfall is larger for large rainfall rates than that predicted by Laws and Parsons. For small rates good agreement is obtained. (See J. O. Laws and D. A. Parsons, "The Relation of Drop Size to Intensity." Trans. Amer. Geophysical Union. p. 452, 1943.)
43.	1957* 3300 MHz 26.7 mi and 46.3 desert Arizona	Due to interference between the diffracted wave and direct wave, an "obstacle gain" can be achieved. Thus, path irregularities can be utilized to increase the signal gain if the microwave terminals are placed at a proper location.
44.	Oct. 56 - Oct. 57 2000 MHz 20.7 mi path Ottawa, Canada	Due to meteorological conditions, deep fades do not occur in colder weather.
45.	Nov. 1954 3982, 4020 MHz 54.8 km, mountain path Japan	Meteorological data indicated that a duct in the vicinity of the transmitter caused fadings at the receivers. The author indicates that fades are caused by interference between a convergent and divergent ray.
46.	1961* band centered at 100 MHz 24 paths	Meteorological data may be used to predict the seasonal variation of radio fields.

*Publication date.

47.	1958, 1959 10 GHz sea path England	At optical ranges the received signal level can frequently be from 5 to 30 db below the level expected in an atmosphere of uniform variation of refractive index with height. When this loss occurs an increase in signal level to a near theoretical value takes place when the range is reduced.
48.	August 1961 1040, 9300 MHz optical, land Colorado	The cross-correlation coefficient of instantaneous carrier envelopes separated by 100 MHz has an overall value of .91. Results support the feasibility of wide band modulation techniques for within-the-horizon paths.
49.	1961* 2880 MHz 2 mi path with trees Texas	The signal strength for vertical polarization behind an obstruction of trees is found to vary with the screening angle (i.e. the smaller the screening angle is, the greater the tree obstruction becomes). For small screening angles the signal strength approaches the theoretical curve for diffraction over a spherical surface. Time variations of the signal are observed to be slow and about 1 to 6 Hz. An approximate point source is distorted when a tree or a portion of a tree is intercepted by the main beam of the receiving antenna. Radars employing beam-comparison techniques are subject to significant pointing errors when a tree or a portion of a tree is intercepted by the main beam of the tracking antenna.
50.	1950 - 1960 1046, 751, 138, 1250, 100, 250, 400 MHz both sea and land Colorado and California	Fadeouts tend to be more frequent but of shorter duration for higher frequencies. Results show a stronger diurnal trend of fadeout incidence in continental climates than in maritime climates. A significant dependence of fadeout characteristics of the refractive index structure has been observed in maritime climates. There are indications that the occurrence of fadeout is correlated on

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vertically spaced antennas. The phenomenon of space-wave fadeouts is observed whenever the refractive index profile has strong low level modification, regardless of climatic conditions and physical causes of the modification.

51. 1964
9293, 9430 MHz
Optical, Land
Colorado

Fading was more pronounced and correlation coefficients were generally lower over the path with the lower beam elevation angle. This is consistent with an increase of sensitivity to horizontal stratification of refractivity on the troposphere at lower beam elevation angles.

52. 1965*
Statistical Study
of centimeter waves

Attenuation by rainfall in the 2 GHz band is of no importance but can become of increasing concern as frequency increases. Experimentally obtained graphs verify this statement.

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*Publication date.

REFERENCES

1. Stratton, J. A., The Effect of Rain and Fog on the Propagation of Very Short Radio Waves, IRE-PROC., Vol 18, June 1930, pp. 1064-1074.

2. Robertson, S. D. and King, A. P., Effect of Rain Upon Propagation of Waves in 1 and 3 cm Regions. IRE-PROC., Vol. 34, April 1946, pp. 178-180.

3. Mueller, G. E., Propagation of 6 mm Waves, IRE-PROC., Vol. 34, April 1946, pp. 181-183.

4. Sharpless, W. M., Measurements of the Angle of Arrival of Microwaves, IRE-PROC., Vol. 34, November 1946, pp. 837-848.

5. Miller, G. A.; Halbert, H. W.; Doherty, L. H.; Swanson, D.A.; Suffield Tropospheric Project, Final Report on Contract JCC/WP/TP. Canadian Radio Wave Propagation Committee, 2 April 1946.

6. Smith-Rose, R. L. and Strickland, A. C.(Miss), An Experimental Study of the Effect of Meteorological Conditions Upon the Propagation of Centimetric Radio Waves: "Meteorological Factors in Radio-Wave Propagation," Physical Society (London, 1946), pp. 18-37.

7. Strickland, A. C. (Miss), Refraction in the Lower Atmosphere and its Applications to the Propagation of Radio Waves, "Meteorological Factors in Radio-Wave Propagation," Physical Society (London, 1946), pp. 253-267.

8. Wickizer, G. S. and Braaten, A. M., Propagation Studies on 45.1, 474, 2800 mcps Within and Beyond Horizon, IRE-PROC., Vol. 35, July 1947, pp. 670-680.

9. Katzin, Bauchman, Binnian, 3 and 9 cm Propagation in Low Ocean Ducts, IRE-PROC., Vol. 35, September 1947, pp. 891-906.

10. Bullington, K., Radio Propagation at Frequencies Above 30 mcps, IRE-PROC., Vol. 35, October 1947, pp. 1122-1136.

11. Durkee, A. L., Results of Microwave Propagation Tests Over a 40 Mile Overland Path, IRE-PROC., Vol. 36, 2 February 1948, pp. 197-205.

12. Wexler, R. and Weinstein, J., Rainfall Intensities and Attenuation of Centimeter Electromagnetic Waves, IRE-PROC., Vol. 36, 5 May 1948, pp. 353-355.

13. Thompson, L. E., Microwave Propagation Experiments, IRE-PROC., Vol. 36, 5 May 1948, pp. 671-676.

14. Hamlin, E. W. and Gordon, W. E., Comparison of Calculated and Measured Phase Difference at 3.2 cm, IRE-PROC., Vol. 36, October 1948, pp. 1218-1229.

15. McPetrie, J. S.; Starnecki, B.; Jarkowski, H.; and Sicinski, L., Oversea Propagation on Wavelength of 3 and 9 Centimeters, IRE-PROC., Vol. 37, March 1949, pp. 243-257.

16. Gough, M. W., V.H.F. and U.H.F. Propagation Within Optical Range, MARCONI REV., Vol. 12, October-December 1949, pp. 121-139.

17. Day, J. P. and Trolese, L. C., Propagation of Short Radio Waves Over Desert Terrain, IRE-PROC., Vol. 38, February 1950, pp. 165-175.

18. Millar, J. F. and Byam, L. A., Jr., A Microwave Propagation Test, IRE-PROC., Vol. 38, 6 June 1950, pp. 619-626.

19. Bussey, H. E., Microwave Attenuation Statistics Estimated from Rainfall and Water Vapor Statistics, IRE-PROC., Vol. 38, July 1950, pp. 781-785.

20. Phillips, W. E., Permittivity of Air at a Wavelength of 10 Centimeters IRE-PROC., Vol. 38, July 1950, pp. 786-790.

21. Boyd, J. E.; Martin, R. A.; Yoe, C.; Brown, F. B.; The Effect of Atmospheric Conditions on the Propagation Characteristics of Electromagnetic Waves in the Microwave Region, Technical Report No. 4, Final Report on Project No. 109-8, Contract No. W28-099-9C-175. Georgia Institute of Technology, State Engineering Station, Atlanta, Georgia. June 30, 1951.

22. Saxton, J. A. and Hopkins, H. G., Some Adverse Influences of Meteorological Factors on Marine Navagational Radar, (Radio and Communications Engr.) Vol. 98, Part III, INSTN. OF ELECT. ENGR.-PROC., January 1951, pp. 26-36.

23. Straighton, A. W.; Metcalf, D. F.; and Tolbert, C. W.; Study of Tropospheric Scattering of Radio Waves, IRE-PROC., Vol. 39, June 1951, pp. 643-648.

24. Ibid.

25. Crawford, A. B. and Jakes, W. C., Jr., Selective Fading of Microwaves, BELL SYSTEM TECH. J., Vol. 31, January 1952, pp. 68-90.

26. DeLange, O. E., Propagation Studies at Microwave Frequencies by Means of Very Short Pulses, BELL SYSTEM TECH. J., Vol. 31, No. 1, January 1952, pp. 91-103.

27. Schulkin, M., Average Radio-Ray Refraction in the Lower Atmosphere, IRE-PROC., May 1952, pp. 554-561.

28. Chavance, Pierre, Etude de la Propagation des Ondes Centrimetriques dans le Nord de la France (Study of the Centrimeter Waves in Northern France), ANNALES DES TELECOMMUNICATIONS, Vol. 7, No. 7, June 1952, pp. 154-261.

44. Hay, D. R., and Poaps, G. E., Prolonged Signal Fade-Out on a Short Microwave Path, CANADIAN J. OF PHYS., Vol. 37, March 1959, pp. 313-321.

45. Ikegami, F., Influence of Atmospheric Duct on Microwave Fading, IRE-TRANSACTIONS ON ANTENNAS AND PROPAGATION, Vol. AP-7, No. 3, July 1959, pp. 252-257.

46. Bean, B. R. and Cahoon, B. A., Correlation of Monthly Median Transmission Loss and Refraction Index Profile Characteristics, J. RES. OF U. S. NAT. BUR. STANDARDS (Radio Propagation), Vol. 65D, No. 1, January-February 1961, pp. 67-74.

47. Kitchen, F. A., John, W. R. R. and Richards, E. G., Some Factors Influencing 3 cm Radio-Wave Propagation Within and Beyond the Radio Horizon, INSTN. OF. ELECT. ENGRS.-PROC. (Radio and Electronic Engr.), Part B, Vol. 109, May 1961, pp. 257-263.

48. Barghausen, A. F.; Barsis, A. P.; Kirby, R. S.; Fading Characteristics and Bandwidth Capability for Within-The Horizons Propagation at 1040 and 9300 mc/s. National Bureau of Standards, Boulder Colorado, August 1961.

49. LaGrone, A. H., and Chapman, C. W., Some Propagation Characteristics of High UHF Signals in the Immediate Vicinity of Trees, IRE-TRANSACTIONS ON ANTENNAS AND PROPAGATION, Vol. AP-9, September 1961, No. 5, pp. 487-491.

50. Barsis, A. P. and Johnson, M. E. Prolonged Space-Wave Fadeouts in Tropospheric Propagation, J. RES. OF. U. S. BUR. STANDARDS (Radio Propagation), Vol. 66D, No. 6, November-December, 1962, pp. 681-693.

51. Gierhart, G. D.; Samson, C. A.; Krinks, R.; Comparison of 9293 and 9430 mc/s Propagation Data Taken Over Long Line-Of-Sight Paths, N National Bureau of Standards, Boulder Colorado, 1964.

52. Medhurst, Richard G., Rainfall Attenuation of Centimeter Waves; Comparison of Theory and Measurement, IEEE-TRANSACTIONS ON ANTENNAS AND PROPAGATION, Vol. AP-13, No. 4, July 1965, pp. 550-563.